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MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

Calculation of Parenchymal Pressure Due to Double Peak Loading

ANNUAL/FINAL REPORT

Michael J. Vander Vorst
James H. Stuhmiller

JANUARY 1990

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21701-5012

Contract No. DAMD17-85-C-5238

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Peak parenchymal pressures, calculated with a one-dimensional model of the structural response of the thorax and lung, are compared with injury observed in sheep exposed to successive blasts a few milliseconds apart. The purpose of this work is to correlate injury level with blast conditions using computer simulations. The calculated peak parenchymal pressure adjacent to the pleural surface varies with blast conditions similarly to the observed increase in lung weight. This suggests that the pressure in the lung parenchyma can be correlated with lung injury.

Results of the calculations using idealized loads support the conjecture that two identical blasts separated by a small time interval are more injurious than a single blast. The predicted parenchymal pressure for two blasts separated by 1.7 ms is larger than for a single blast, even though the peak incident pressures for the dual and the single blasts are identical. (JES)

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19. ABSTRACT *(Continued from front)*

CALCULATION OF PARENCHYMAL PRESSURE DUE TO DOUBLE PEAK LOADING

Michael J. Vander Vorst
James H. Stuhmiller

Applied Science and Engineering Technology
JAYCOR

ABSTRACT

Peak parenchymal pressures, calculated with a one-dimensional model of the structural response of the thorax and lung, are compared with injury observed in sheep exposed to successive blasts a few milliseconds apart. The purpose of this work is to correlate injury level with blast conditions using computer simulations. The calculated peak parenchymal pressure adjacent to the pleural surface varies with blast conditions similarly to the observed increase in lung weight. This suggests that the pressure in the lung parenchyma can be correlated with lung injury.

Results of the calculations using idealized loads support the conjecture that two identical blasts separated by a small time interval are more injurious than a single blast. The predicted parenchymal pressure for two blasts separated by 1.7 ms is larger than for a single blast, even though the peak incident pressures for the dual and the single blasts are identical.

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EXPERIMENTAL RESULTS

Lung injury from successive blasts separated by small time intervals has been measured by Richmond[1]. Two 8 lb TNT charges separated by a vertical steel plate were detonated at intervals from 0 to 14 ms. Sheep were placed 11 feet from the charges and instrumented with a pressure gauge in the esophagus. Free field pressures were measured. After each shot the weight of each lung and the animal's weight was recorded. In addition lung weights and total weight for each of a group of control animals were measured. The severity of lung hemorrhag^ was established visually and quantified by the lung weight as a percentage of body weight. By this measure, injury was considerably greater for two charges detonated simultaneously than for a single charge. When two charges were detonated successively, lung injury was much less than for a simultaneous detonation but still greater than for a single charge.

MODEL DESCRIPTION

The computer program, THOR, used in these calculations is a one-dimensional, compressible, Lagrangian, finite-difference, computer program constructed to model the dynamics of the thorax.[4] The geometry modeled in these calculations is a line just below the seventh thoracic vertebrae of the animal which extents from the right rib surface through the esophagus to the left rib surface. The pressure loading on the ribs was estimated from knowledge of the free field pressure from Richmond's experiments.

The key parameters needed for calculations and their assumed values are:

ambient pressure	= 82.0 kPa
mass of rib-muscle-skin layer	= 1.65 g/cm^2
lung composite density	= 0.2 g/cm^3
Friedlander pressure loading	

$$P(t) = P_r(1 - t/T_r)\exp(-b_r t/T_r)$$

where

P_r is the maximum pressure load on the thorax,

T_r is the positive duration of the load,

I_r is the positive impulse of the load,

b_r is related to the shape factor

$$S = I/(PT)$$

through the relationship

$$S=(1-(1-e^{-b})/b)/b.$$

Richmond reports the incident pressure, duration and impulse, P_s, T_s, I_s, for both peaks from the free field gauges. The reflected pressure is given from the incident by the expression[2]

$$P_r = (P_s + P_o)\frac{(2+\alpha)s - 1}{\alpha + s} - P_o$$

where

$$s = (P_s + P_o)/P_o$$

$$\alpha = \frac{1}{\mu^2} = \frac{\gamma + 1}{\gamma - 1},$$

where γ, the specific heat ratio, depends on the peak overpressure but for simplicity we use

$$\gamma = 1.4.$$

Impulse and duration of the reflected pulse, however, are more difficult to estimate. For these calculations we make the assumption that the duration, and shape factor, are the same for both the reflected and incident waves. Data from sheep taken in the summers of 1985 and 1986 indicate that the reflected duration and shape factor are usually smaller than the incident.[3]

In some cases, the experimental incident pressure for the second peak appears to be a narrow spike. In these cases, lower values were inferred directly from the pressure traces. Table 1 and 2 give all of the parameters used for each case.

Since only the blast side parenchymal pressure was of interest in this study, no loading was applied to the side of the animal opposite the blast

MODEL RESULTS

Peak intrathoracic pressures are compared to lung injury, results in Table 3. Increase in right lung weight is defined as

$$\text{Increase Factor} = \frac{W_t - W_c}{W_c}$$

Table 1. Measured Incident Parameters and Estimated Loads in First Peak

Measured Incident Parameters: Separation Time ms	Pressure Ps kPa	Impulse Is kPa-ms	Duration Ts ms	Friedlander Exponent b	Estimated Load Pr kPa
Single	215	NA	1.2	0.5	780
0.0	415	NA	1.5	0.5	1875
1.7	260	172	1.5	0.5	1000
3.6	260	160	1.6	0.5	1000
5.5	260	151	1.4	0.55	1000
7.5	260	169	1.5	0.55	1000
9.7	260	175	1.7	0.7	1000
11.6	260	165	1.5	0.6	1000
13.6	260	165	1.5	0.3	1000

Table 2. Measured Incident Parameters and Estimated Loads in Second Peak

Measured Incident Parameters						
Separation Time ms	Pressure Ps kPa Reported	Pressure Ps kPa Adjusted	Impulse Exponent Is kPa-ms	Duration Ts ms	Fried-lander Exponent b	Estimated Load Tr kPa
1.7	250	250	139	1.3	0.5	895
3.6	345	260	165	1.4	1.0	1000
5.5	440	260	154	1.2	0.5	1000
7.5	418	325	150	1.2	0.9	1360
9.7	418	295	185	1.2	1.5	1200
11.6	377	335	154	1.0	1.5	1400
13.6	311	295	139	1.3	1.5	1200

Table 3. Increase in Measured Right Lung Weight and Calculated Blast Side Pleural Pressure

Separation Time ms	Blast Side Pleural Pressure kPa	Measured Percent Right Lung %	Measured Increase in R. Lung Weight Factor
Single	133	0.55	0.38
0.0	544	1.35	2.38
1.7	305	0.69	0.72
3.6	271	0.63	0.58
5.5	212	0.72	0.80
7.5	258	0.59	0.47
9.7	300	0.58	0.45
11.6	220	0.73	0.82
13.6	248	0.64	0.60

where

W_t is the right lung weight after blast exposure as a percentage of body weight, and

W_c is the average right lung weight percentage for the control group.

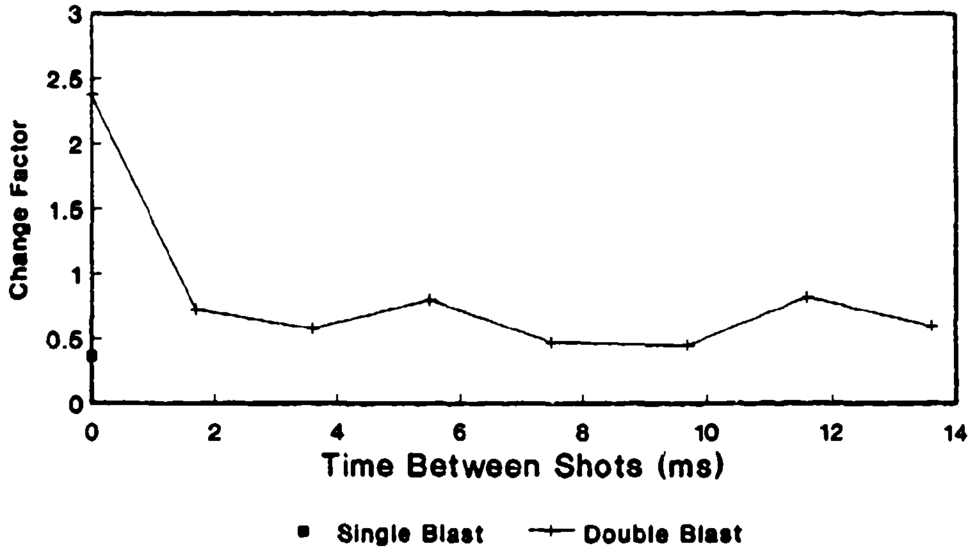
Richmond reported a right lung weight percentage, W_c, of 0.4% for the control animals in this test. Figure 1 presents plots of increase in right lung weight and peak right parenchymal pressure. The two curves behave similarly. Calculated peak esophageal pressures are compared with the measured values in Figure 2. Figure 3 presents the transient solution from the THOR calculation for the 1.7 ms case. Plots of the load, right rib dynamics, and four intrathoracic locations are given.

The loadings for these calculations was inferred from the measured incident pressure traces. Unfortunately, as seen in Table 1, there is a large shot to shot variation in the incident pressures, impulses and positive durations. In particular, the first peak of the separated double blasts is significantly larger than the peak of the single blast. Hence, for these experiments, the injury from the double blasts is always larger than from the single blast. Based on these results, it is difficult to draw conclusions about the injury induced by complex waves compared to simple ones.

However, calculations using idealized loading conditions suggest that complex waves could be more injurious than simple ones. The pressure waveform describing the blast loading was assumed to be identical for the single blast and each of the double blasts. Figure 4 shows the peak parenchymal pressure for each time interval when the idealized loadings are used. These calculations predict, as before, that the blast side parenchymal pressure is larger for the double peak waves than for the single wave for short separation times. For large separation times, however, the peak parenchymal pressure due to the double blast approaches that for the single blast.

Inspection of the calculated right parenchymal pressure shown in Figure 5 leads to a mechanical explanation of the cumulative affect of the two waves. Even though the load signal shows two distinct waves, the intrathoracic pressures exhibit an additive effect. The blast loading on the skin displaces the ribs which in turn presses against the lung to set up a pressure wave in the parenchyma. The duration of the parenchymal wave is larger than the duration of the load due to the inertia of the ribs. Hence, if the time between two waves in the load is small enough, the second wave strikes the rib while the parenchyma near the pleura is still under compression. This further displaces the rib and causes the pressure to increase to a new peak which is higher than the first. When the time between waves is several times greater than the duration of the load, the parenchymal waves are distinct and of equal amplitude, and the peak parenchymal pressures for the double and single waves are nearly the same.

Increase in Weight of Right Lung in Double Peak Study



Calculated Right Pleural Pressure in Double Peak Study

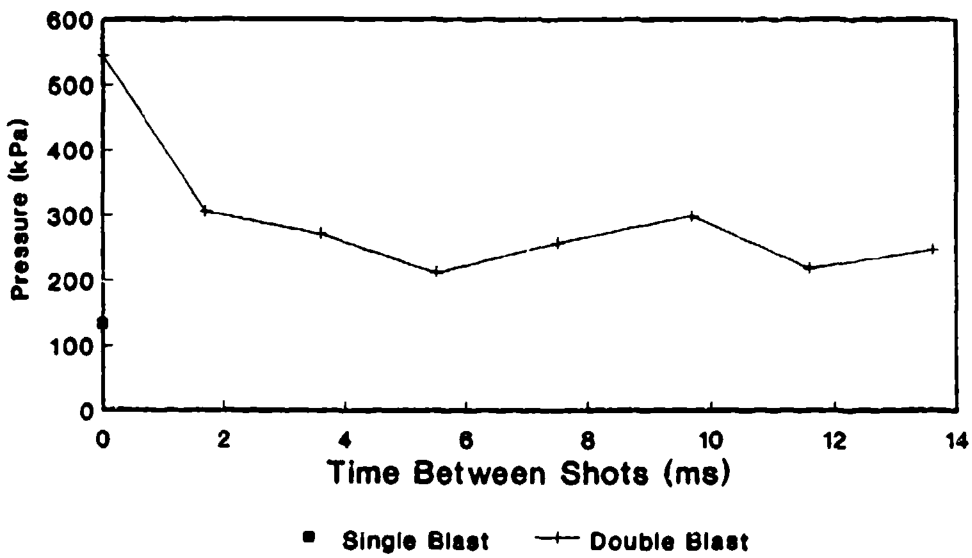


Figure 1. Comparison of increase in lung weight with intrathoracic pressure.

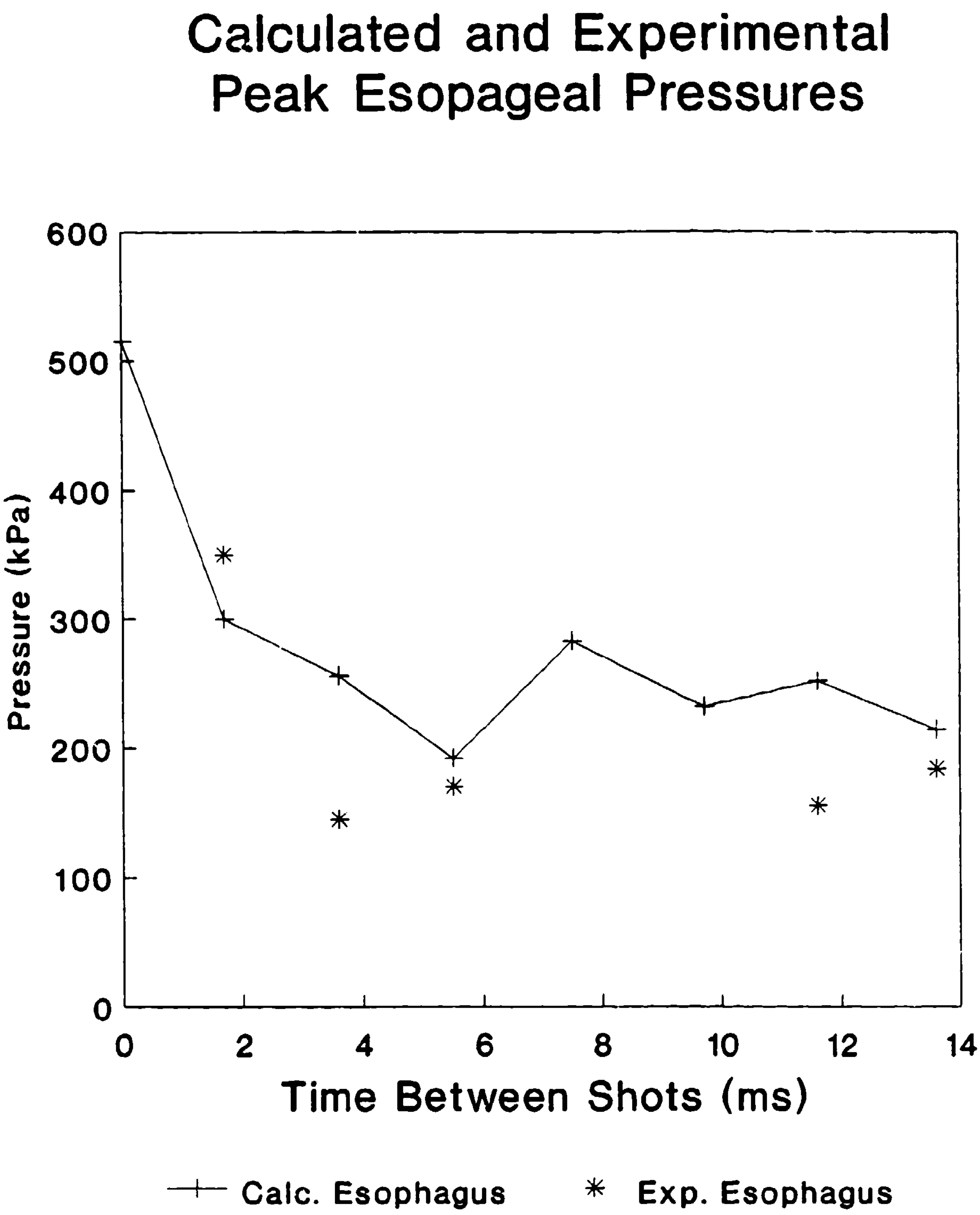


Figure 2. Comparison of calculated and experimental intrathoracic pressure.

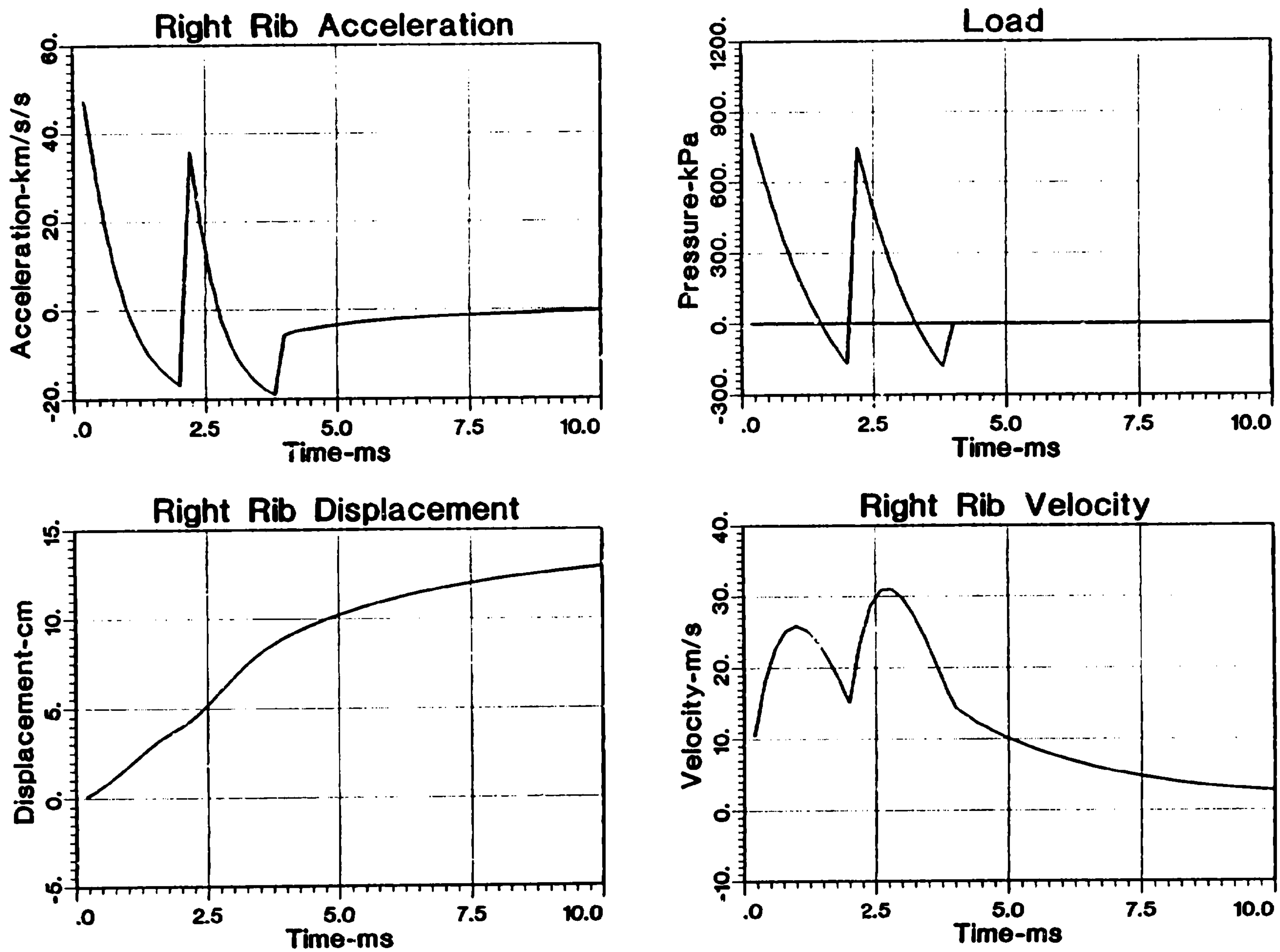


Figure 3a. Calculated results for two blasts at 1.7 ms interval.

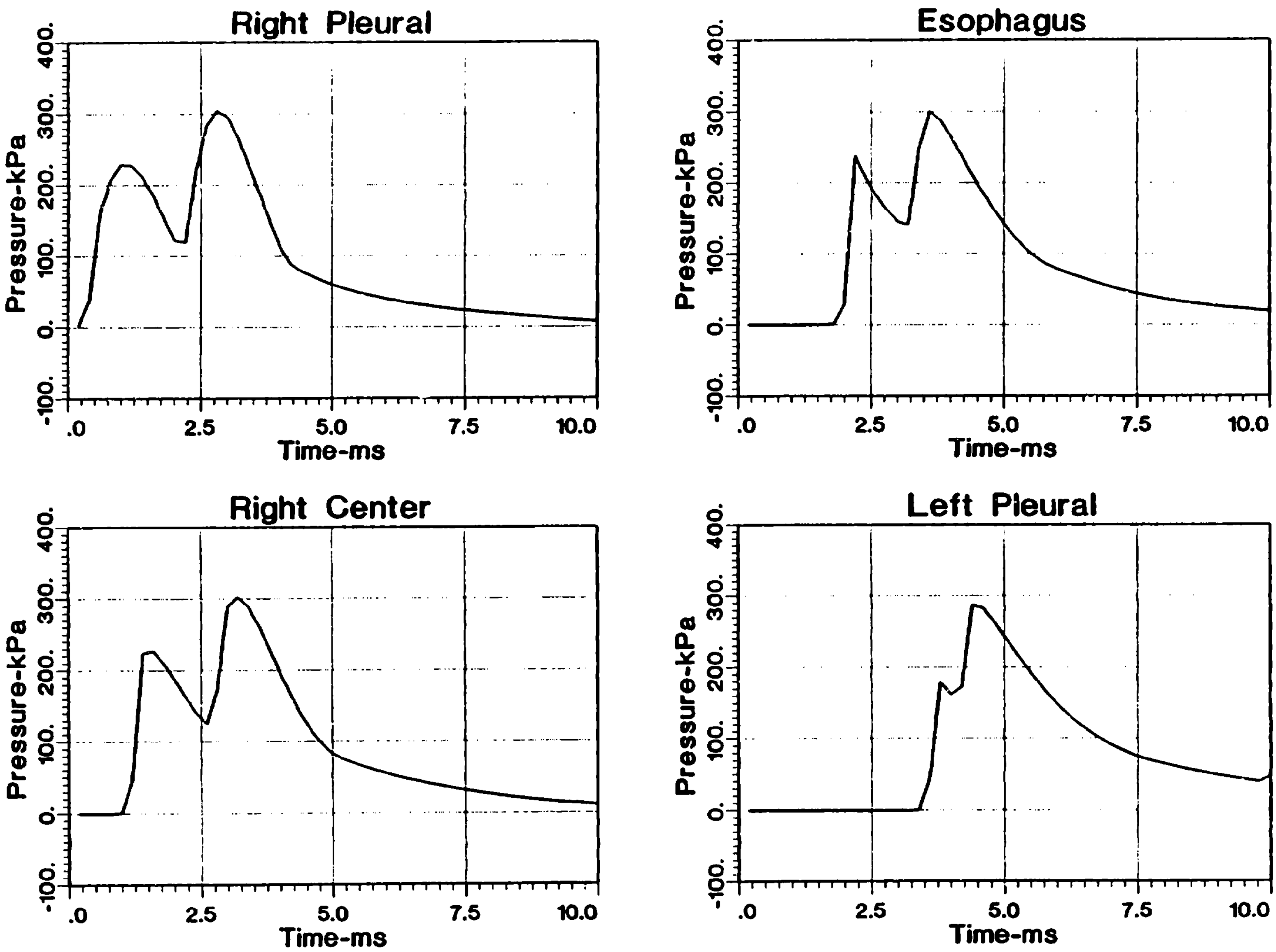


Figure 3b. Calculated results for two blasts at 1.7 ms interval.

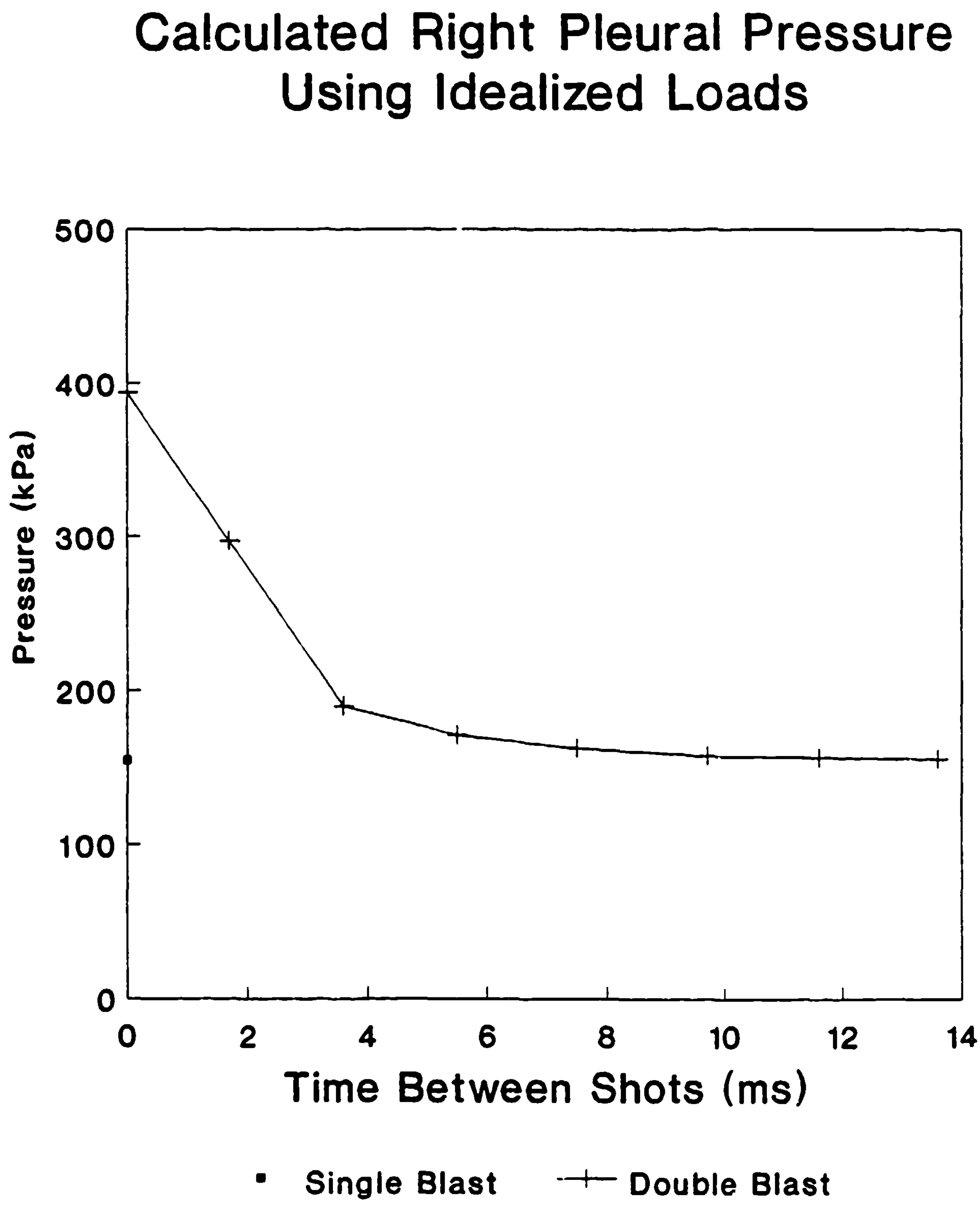


Figure 4. Calculated intrathoracic pressure using idealized loads.

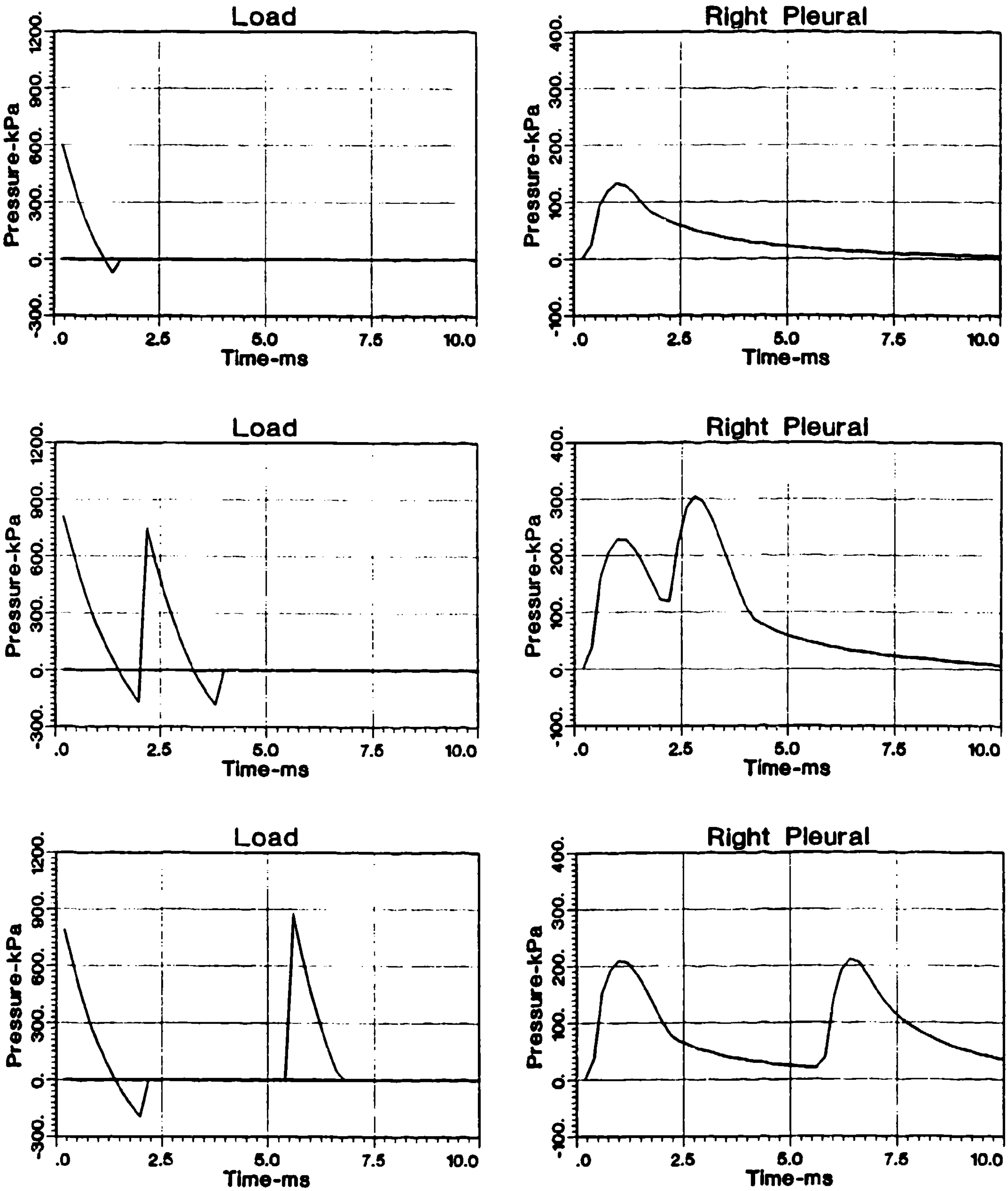


Figure 5. Load and intrathoracic pressure vs. time for single blast and blasts at 1.7 ms and 5.5 ms intervals.

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